DCIEM CR 2001-005

AN INVESTIGATION OF CURRENT AND ALTERNATIVE METHODS FOR TESTING THE WATERPROOFNESS OF DRY SUITS

FINAL REPORT

by

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PWGSC Contract No. W7711-6-7479-04

on behalf of
DEPARTMENT OF NATIONAL DEFENCE

as represented by
Defence and Civil Institute of Environmental Medicine+
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Original submitted Sept 21, 2000. Revised Jan 31, 2001.

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Résumé

Des combinaisons étanches sont portées par le personnel de différents organismes civils pour une protection contre une exposition à l'eau pendant l'immersion. La protection contre la contamination chimique et biologique et l'isolation de l'eau froide dépendent de l'intégrité de l'étanchéité d'une combinaison. Les combinaisons étanches peuvent exiger un contrôle afin de vérifier leur intégrité pendant leur fabrication et leur emploi. Quoiqu'il existe de nombreuses méthodes d'essai d'étanchéité normalisées pour les éprouvettes de tissu, seulement quelques-unes existent pour les combinaisons. La revue de la documentation a indiqué que les essais des combinaisons d'immersion sont généralement effectués en remplissant d'eau la combinaison et en inspectant l'extérieur pour voir si de l'eau s'échappe ou en la remplissant de gaz sous pression, en rinçant l'extérieur avec de l'eau savonneuse, puis en l'inspectant afin d'y déceler la formation de bulles. Le rapport décrit en détail une enquête sur quatre autres méthodes de détection de fuite pour les combinaisons.

Sommaire

Des combinaisons étanches sont portées par le personnel de plusieurs organismes civils pour la protection contre l'exposition à l'eau durant l'immersion. La protection contre la contamination chimique ou biologique et l'isolation de l'eau froide dépendent de l'intégrité de l'étanchéité d'une combinaison. Les combinaisons étanches peuvent nécessiter un contrôle afin de vérifier leur intégrité pendant la construction et l'usage. Bien qu'il existe de nombreuses méthodes normalisées d'essai d'étanchéité pour les éprouvettes de tissu, seulement quelques-unes existent pour les combinaisons étanches. Le rapport suivant décrit en détail une enquête financée par IMED et IES sur d'autres méthodes d'essai d'étanchéité pour les combinaisons.

La revue de la documentation a indiqué que les essais types sur des combinaisons d'immersion sont effectués soit en remplissant d'eau la combinaison et en inspectant l'extérieur pour voir si l'eau s'échappe ou en la gonflant avec du gaz sous pression, en rinçant l'extérieur avec de l'eau savonneuse puis en l'inspectant afin d'y déceler la formation de bulles. La revue a indiqué également que c'est l'équation de Laplace qui décrit le mieux la pénétration de liquide dans les milieux poreux. La théorie et les expériences menées sur différentes membranes révèlent que les trous qui préoccupent les plongeurs sont de l'ordre aussi petit que 5 μm de diamètre.

L'essai de membranes de filtration de dimension de pores connue et de tissus de combinaisons étanches à trous pré-amorcés a démontré que la pression d'air à laquelle les trous sont décelables par formation de bulles était plus élevée que la pression hydrostatique requise pour déceler la fuite d'eau. La différence de pression était plus élevée avec du nylon enduit de polyuréthane et un stratifié de tissu aramide PTFE que la mousse de néoprène et le caoutchouc vulcanisé, ce qui a des répercussions sur les méthodes d'essai actuelles de gonflement des combinaisons avec de l'air à des pressions comprises entre 0,2 et 0,5 lb/po^2. Il est recommandé que les pressions d'air utilisées dans les essais à l'eau savonneuse dépassent la pression hydrostatique à laquelle le tissu est soumis dans l'usage réel. Dans nombre de cas, la chose est impossible sans risquer d'endommager la combinaison pendant l'essai.

Quatre autres méthodes de détection des fuites ont été examinées. La visualisation de Schlieren et l'imagerie thermique ont toutes les deux échoué à fournir une image de l'air

EXECUTIVE SUMMARY

Dry suits are worn by personnel from various civilian agencies for protection against exposure to water during immersion. Protection against chemical/biological contamination and insulation from cold water rely on the integrity of a suit's waterproofing. Dry suits may require test inspection to verify their integrity during both construction and actual use. While there are numerous standard leak test methods for fabric swatches, only a few exist for full suit systems. The following report details a DCIEM-TIES-funded investigation into alternative leak testing methods for dry suits.

Literature review indicated testing of immersion suits is typically conducted by either filling the suit with water and inspecting its exterior for liquid breakthrough or by filling it with pressurized gas, rinsing its exterior with soapy water and inspecting for bubble formation. The review indicated penetration of liquid through porous media is best described by Laplace's equation. Theory and experiments conducted on various membranes suggest that the smallest holes of concern to a diver are the order of 5 um in diameter.

Testing filtration membranes of known pore size and dry suit materials with induced holes indicated the air pressure at which holes were detectable by bubble formation was greater than the hydrostatic pressure required for water leakage. This difference in pressure was greater with polyurethane-coatednylon and an aramid-PTFE laminate than neoprene foam and vulcanized rubber. This has implications to existing test methods which inflate suits with air to pressures between 0.2 and 0.5 psi and apply soapy water. In actual use, these suits can be subjected to hydrostatic pressure differentials in excess of 2 psi. It is recommended that air pressures used for soapy water testing, exceed the hydrostatic pressure for which the material is subjected to in actual use. In many cases, this is not possible without the risk of inducing suit damage during the test.

Four alternative leak detection methods were investigated. Schlieren visualisation and thermal imaging both failed to provide an image of air or argon gas exiting a leak. Heating either gas 20C above ambient and increasing pressure to 1 psi did not permit visualisation. Passive ultrasonic was capable of detecting leaks in fabric but required high inflation pressures (2 - 5 psi). Active ultrasonics was better at detecting holes, but only those through thin materials. It did not work with thicker neoprene suits. Detection of argon gas by thermal conductivity means was the only alternative approach to fabric leak detection found worthy of further investigation. A hand-held gas detector was capable of finding small leaks (10–30 um) at pressures as low as 0.1 psi (5 mmHg), although its probe had to remain in close proximity to the leak (15 mm above hole; 5 mm laterally). A full-scale suit leakage test chamber based on argon detection was designed and constructed. Suit tests indicated three main deficiencies with the chamber: dilution of argon gas to undetectable levels, lengthy detector response time and a tendency for argon to settle to the chamber bottom. Recommendations for improving the current chamber are provided.

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Abstract

Dry suits are worn by personnel from various civilian agencies for protection against exposure to water during immersion. Protection against chemical/biological contamination and insulation from cold water rely on the integrity of a suit's waterproofing. Dry suits may require test inspection to verify their integrity during both construction and actual use. While there are numerous standard leak test methods for fabric swatches, only a few exist for full suit systems. Literature review indicated testing of immersion suits is typically conducted by either filling the suit with water and inspecting its exterior for liquid breakthrough or by filling it with pressurized gas, rinsing its exterior with soapy water and inspecting for bubble formation. The report details an investigation into four alternative leak detection methods for dry suits.

TABLE OF CONTENTS

EXECUTIVE SUMMARY i

TABLE OF CONTENTS ii

1.0 BACKGROUND 1

2.0 INTRODUCTION 2

3.0 METHODS AND RESULTS 3

1.1 Theoretical Investigation of Leakage 3
1.2 Practical Investigation of Leakage 5
1.3 Small Scale Testing of Alternate Leakage Detection Methods 11

1.3.1 Schlieren Visualisation 11
1.3.2 Thermal Imaging 14
1.3.3 Ultrasonics Detection 17
1.3.4 Trace Gas Detection 19

1.4 Full Suit Testing 22

2.0 DISCUSSION 25

3.0 CONCLUSIONS 27

4.0 RECOMMENDATIONS 28

7.0 REFERENCES 29

1.0 BACKGROUND

Mustang Survival Corporation was tasked on Oct 28, 1999 with a call-up against a Technical Investigation and Engineering Support (TIES) standing offer contract [1]. The call-up entitled "*An Investigation of Current and Alternative Methods for Testing the Waterproofness of Dry Suits*" was the result of a request for proposal made by the Defence and Civil Institute of Environmental Medicine (DCIEM) on August 6, 1999 [2].

The following is an extract from the tasking's Statement of Work (SOW):

1. Review literature on existing leakage test methods and alternative technologies potentially applicable to leak testing of diving and immersion dry suits.
2. Submit a draft experimental plan with detailed procedures and data analysis to the scientific authority for comment and approval.
3. Conduct a theoretical and practical investigation of the mechanisms for leakage in order to define and quantify critical parameters (e.g. pressure differentials required to accurately test for water leakage, minimum hole sizes that allow water leakage at these pressure differentials, relationships between leakage of water and diffusion of various gases, effect of surfactant type and concentration, effect of liquid transport via wicking on leakage, etc.).
4. Perform leakage tests on leaky diving and immersion suits built from relevant materials (coated and/or laminated fabrics and closed-cell foams) using Mustang Survival's existing pressurized air and soapy water leak test apparatus. The suits will have different sized leaks at various locations (i.e. seams and punctures in base fabric) and will be tested at various air pressure differentials. Investigate the effect of soap type and concentration on leak detection.
5. Build small-scale versions of test apparatus necessary to investigate each of the five alternate approaches to leak testing (moisture sensor-equipped manikin, trace gas detection, thermal imaging, Schlieren visualization and ultrasonics). Testing is to be conducted with the same leaky suits used for the pressurized air and soapy water tests. Use each apparatus in a manner that allows for direct comparison to the existing pressurized air and soapy water method. Assess the pros and cons of each test method.
6. Compile a final report detailing the work conducted. The report shall provide results of the literature review and theoretical investigation. The report shall detail each of the test apparatus and provide a comparative assessment of the results obtained from each method. The report shall indicate which method best ensures a dry suit's waterproof integrity and provide recommendations for potential improvements to leakage test methods.

Note: Investigation of a moisture sensor-equipped manikin (SOW item 5) was not pursued at the request of the TIES contract's Technical Authority.

2.0 INTRODUCTION

Dry suits are worn by personnel of various civilian agencies as a means of providing protection against exposure to water during immersion. Protection against chemical/biological contamination and insulation from cold water rely on the integrity of the dry suit's waterproofing. A dry suit may require inspection and testing to verify this integrity during both initial construction and actual use.

While there are various accepted approaches to testing for leakage through fabric swatches, there are only a few methods for assessing full suit systems. These tend to be applicable to medical and hazardous material garments, which typically protect against spills and spray rather than full immersion in water.

There are two methods commonly used by industry and military for assessing the waterproof integrity of dry suits designed for immersion protection. One method is used by both Mustang Survival Corporation and the Canadian Forces for aircrew immersion coveralls; the other method is used by the United States Navy. The former method involves turning the dry suit inside out then closing its waterproof zippers and clamping sealed its wrist and neck cuffs (and any other possible openings). The suit is internally pressurised with air and soapy water is liberally applied to its exterior. The occurrence and location of any leakage is detected visually, indicated by the formation of bubbles. The latter method also involves turning the dry suit inside out, closing its waterproof zippers and clamping sealed its wrist and neck cuffs. This method differs from that used by the CF since the suit is filled with water rather than pressurised air. The suit must be held inside a rigid rotating framework, in order to aid inspection (rotation) and restrict suit expansion. Leakage is located visually by the presence of moisture on the suit surface.

Each of these methods has potential faults. Both methods are completely reliant on the visual acuity of the tester. This brings into question the repeatability of the test method and as a result the integrity of a suit at any instant. Neither method is readily portable and both render the suit wet. In a production environment, drying is time-consuming and hence costly. For the user, this wait may invoke the need for additional spare suits. Not all bubble formations observed with pressurised air-soapy water testing are indicative of actual pathways for water leakage. Pressurisation can simply expel air trapped in seams giving a false indication of leakage, or worse, compress materials and seal water pathways giving a false indication of a garment's waterproof integrity. Pressurisation with either air or water can damage the suit, particularly, at its seams, stretchable seals and socks. The pressurised water method requires a support frame and additional belts and strapping to constrain outward expansion.

In light of such deficiencies, four potentially alternative methods for detecting leakage through swatches of material and complete dry suits were investigated. The following report provides technical detail on this investigation.

3.0 METHODS AND RESULTS

The following sections detail the methods used and results obtained during this TIES investigation.

3.1 Theoretical Investigation of Leakage

A literature review was conducted to determine existing leakage detection methods. Only methods known to be applicable to fabrics or garments were reviewed. It was determined that there are very few standards, if any, that apply to the design and manufacture of immersion suits. The few existent standard leak test methods for chemical protective suits were reviewed.

The test method currently used by the Canadian Forces for their Aircrew Anti-Exposure Immersion Coverall (NSN 8475-21-907-9901) involves inflation of the suit with air and application of soapy water. The US Navy method (NAVAIR 17-15GB-504) used on the CWU-62/P involves filling the suit full of water. The shortcomings of both methods (as described in original SOW and proposal [1,2] and the Introduction of this report) combined with the lack of a standardized test method for CF divers dry suits formed the basis for proposing this work.

ASTM F1154-99a "*Qualitatively Evaluating the Comfort, Fit, Function, and Integrity of Chemical-Protective Suit Ensembles*" is completely qualitative and involves a simple visual inspection for suit and seam degradation not a pressurized test. It simply cites methods F1052 and F1359. This method was therefore deemed irrelevant to our intended application.

ASTM F1052-97 "*Standard Test Method for Pressure Testing Vapor Protective Ensembles*" measures the ability of a vapor protective ensemble, including seams, and closures, to maintain a fixed, positive pressure. It is not intended for functional testing of exhaust valves fitted to the suit and does not provide localization of the leak.

ASTM F1359-99 "*Standard Test Method for Liquid Penetration Resistance of Protective Clothing or Ensembles under a Shower Spray while on a Mannequin*" tests the ability of a chemical protective suit ensemble to resist liquid penetration in the form of a shower spray with surfactant treated water. The hydrostatic pressures and spray coverage involved are not representative of the extremes encountered by immersion or diving suits.

Our literature search found many existent standards related to permeation and penetration leak testing of fabric swatches but not full suit systems. ASTM F903-99 "*Resistance of Materials Used in Protective Clothing to Penetration by Liquids*" is the method commonly used for investigation of materials exposed to continuous contact with a chemical. This method was recently used by Mustang Survival during a TIES tasking entitled "*Resistance of Five Polluted Water Diving Suits to Abrasion and Chemical Contamination through Fabric Abrasion*" [3]. The method relies on visual detection of liquid penetration.

ASTM F739-99a "*Resistance of Protective Clothing Materials to Permeation by Liquids or Gases under Conditions of Continuous Contact*" has been used by Gates to assess chemical and biological resistance of their Pro-AM and Pro-HD dry suits [4]. ASTM F1671 "*Standard Test Method for Resistance of Materials Used in Protective Clothing to Penetration by Blood Borne Pathogens using Phi-X174 Bacteriophage Penetration as a Test Method*" has also been used by Gates. F1671 is similar to ASTM F1670 "*Standard Test Method for Resistance of Materials Used in Protective Clothing to Penetration by Synthetic Blood*".

ASTM D5151-99 "*Standard Test Method for Detection of Holes in Medical Gloves*" states that "the smallest hole size that will allow water leakage in a medical glove has not been determined and is beyond the scope of this test method".

We also conducted a literature review of the physical parameters considered critical for the occurrence of water penetration through textile structures. Fluid penetration through materials is commonly described by a capillary bundle model using Laplace's equation [5].

$$R = 2\cdot(\cdot\cos(2)/P$$

Laplace's equation indicates that the minimum pore radius, R, which pressurized liquid water will penetrate is a function of the pressure differential, P, the liquid surface tension, (, and the liquid/material contact angle, 2.

The maximum pressure differential, P, that a given dry suit fabric or system can withstand depends on the fabric type and the suit construction methods. Certain fabrics used on immersion dry suits can be damaged by exposure to large hydrostatic or air pressure differentials. For experimental purposes, it was desirable to apply pressures representative of those experienced in the actual diving environment. A size extra-large CF diver with a height of 74" (188 cm) immersed vertically up to the hollow at the base of their neck has approximately 60" (152 cm) of their body submerged. This would place a maximum static pressure differential of 2.2 $lb\cdot in^{-2}$ (15 $kN\cdot m^{-2}$) across the fabric at their feet. It is possible that dry suits will experience greater dynamic pressure differentials during actual use. This may occur when the wearer enters the water from a height, uses moving vessels for deployment or retrieval, improperly inflates their dry suit, experiences waves and currents or conducts rapid movements. The magnitude and profile of such pressure events are unknown. Upon water entry, a suit is typically compressed hence rapidly vents itself via valves or cuffs due to the increased internal pressure. While this may unseat a wrist or neck seal and allow water ingress, this leakage mechanism was not considered to be within the scope of the current investigation, which limited pressure differentials to 2.2 psi.

The minimum pore radius, R, for leakage through a given material will depend on water surface tension and contact angle as well as pressure. Due to their dependence on material type, contact angles for pure water and various materials were reviewed.

Figure 1 shows the theoretical minimum pore size as a function of pressure for pure water ((= 0.073 $N \cdot m^{-1}$) with polytetrafluoroethylene (2 = 108°) and nylon (2 = 71°) [6].

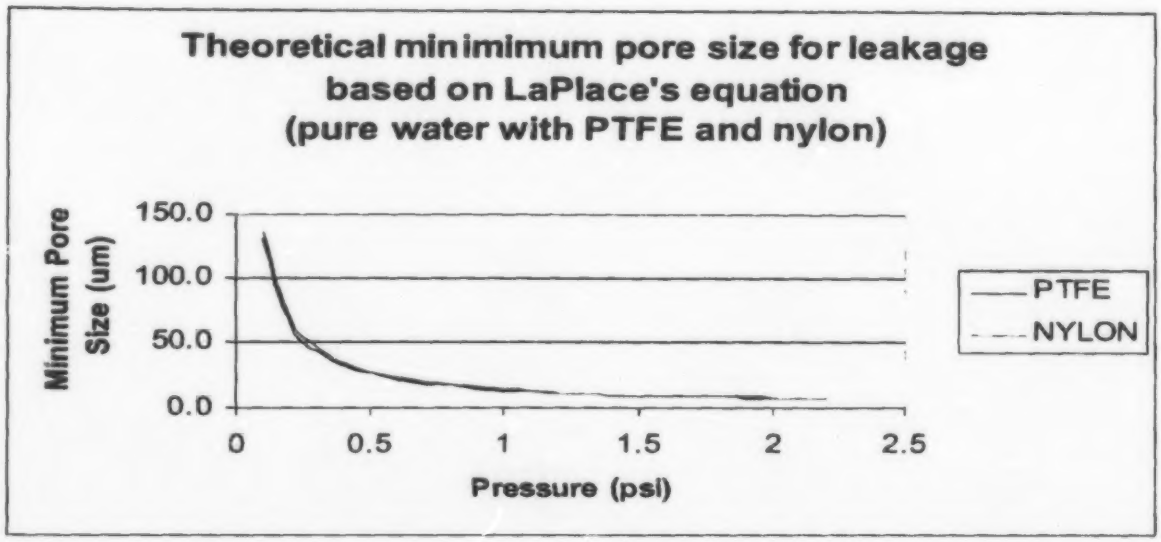

Figure 1 – Theoretical minimum pore size for leakage of pure water through two materials

The results suggest that holes greater than approximately 5 um in diameter may permit leakage of water through fabric during immersion.

3.2 *Practical Investigation of Leakage*

It was suggested that preliminary experiments be conducted to gain practical insight into the relationship between minimum pore size and material for leakage at pressures of up to 2.2 psi (15 $kN \cdot m^{-2}$). Membranes of known pore size and indicative of material used in dry suits were acquired. Unfortunately, due to a lack of readily available membranes, it was not possible to obtain samples of all relevant materials with a complete range of pore size deemed of interest to this study (5.0 um to 200 um).

The membranes were tested for water leakage by placing them in a hydrostatic leak test cell (Figure 2) capable of securing a 4.5" inner diameter (11.4 cm) swatch and subjecting it to water pressure up to 5 psi (34.5 kPa). Water pressure was increased slowly until liquid break through was noted visually. The pressure at which break through occurred was recorded (Table 1). Two trials were conducted per membrane.

The membranes were then tested for leakage by placing them in an air leak test cell (Figure 3) capable of securing a 4.5" inner diameter (11.4 cm) swatch and subjecting it to air pressures up to 5 psi (34.5 kPa). A soap and water solution (2% Ivory™ liquid by weight) was applied liberally to the surface of the membrane with a spray bottle. Air pressure was increased slowly until the onset of bubble formation was noted visually. This air pressure was recorded (Table 1). Two trials were conducted per membrane.

Figure 2 – Hydrostatic leak test cell

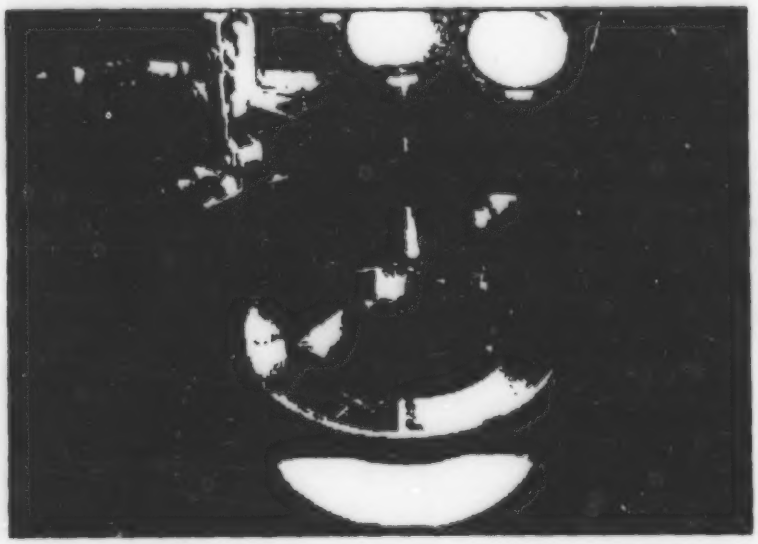

Figure 3 – Air leak test cell

Table 1 – Various membranes of known porosity

Membrane material	Pore size (um)	Minimum hydrostatic pressure* (psi)	Minimum air pressure** (psi)
Polytetrafluoroethylene	0.2	>5.0 ± 0.1	>5.0 ± 0.1
Polytetrafluoroethylene	1.0	>5.0 ± 0.1	>5.0 ± 0.1
Mixed cellulose ester	5.0	0.1 ± 0.1	0.8 ± 0.1
Nylon – Spectra™	10	0.1 ± 0.1	0.3 ± 0.1
Nylon – Spectra™	60	0.1 ± 0.1	0.1 ± 0.1
Fluorocarbon - Spectra™	70	0.1 ± 0.1	0.1 ± 0.1
Nylon – Spectra™	100	0.1 ± 0.1	0.2 ± 0.1

* - Visual observation of water penetration

** - Visual observation of soap bubble formation (Ivory™ liquid soap - 2% by weight)

Based on theory, 0.2 and 1.0 um PTFE membranes should not allow leakage until hydrostatic pressures of 52 and 12.5 psi, respectively. While we were unable to test at such high pressures, we were able to verify the material was waterproof to hydrostatic pressures in excess of 5 psi (our apparatus's maximum), as expected theoretically. When soapy water solution was applied, neither membrane displayed bubble formation even at air pressure in excess of 5 psi (our apparatus's maximum). There was no discrepancy between the pressure for water penetration and bubble formation for these two PTFE membranes.

According to Laplace's equation, a 5.6 um PTFE or nylon membrane should just begin to leak water at our established maximum test pressure of 2.2 psi. While a PTFE membrane with this pore size was not readily available commercially, we were able to obtain a mixed cellulose ester membrane with a pore size of 5.0 um. Testing indicated that this membrane leaked water at a hydrostatic pressure less than 0.1 psi. This is considerably less than expected with PTFE or nylon. It is speculated that the discrepancy is due to the contact angle of water with mixed cellulose being considerably different from that of PTFE or nylon. The contact angle between this membrane and water is unknown. It was noted that the cellulose membrane was hydrophilic and became extremely fragile when saturated. When sprayed with soapy water and exposed to air pressure, bubble formation was not observed up to 0.8 psi. We could not establish when actual bubble formation would occur as the membrane burst at 0.8 psi. It is interesting to note the pressure at which leakage was detected using pressurized air with soapy water was considerably greater than that detected with hydrostatic means. This finding suggests that a pore of 5.0 um may leak water at low pressure yet not be detectable with soapy water unless the air pressure is significantly higher. Most immersion suits are tested with soapy water at a maximum air pressure of 0.2 psi hence such leaks may go undetected.

According to Laplace's equation, a nylon-Spectra™ membrane with a pore size of 10 um would be expected to leak water at 1.4 psi. It was found to leak water at <0.1 psi, considerably less than expected from Laplace's equation. When tested with air and soapy water, air pressure of 0.3 psi was required to observe bubble formation. Again, this indicates a leak of this magnitude may go unnoticed with soapy water testing at traditional garment test pressure. Nylon-Spectra™ membranes with a pore size of 60 and 100 um were expected to leak water at 0.20 and 0.14 psi, respectively. They were both found to leak water at less than 0.1 psi, which is within experimental error of the theoretical pressure. When tested with soapy water at air pressures less than 0.2 psi, bubble formation was detected. The same results were obtained with the 70 um fluorocarbon-Spectra™ membrane.

Materials commonly used in diving dry suits and immersion suits, which are either currently used by or are of interest to the Canadian Forces [3,4], were investigated in a similar manner as the membranes described above (Table 2). Samples of vulcanized rubber (Viking Pro®), aramid-PTFE used on the CF aviation coverall (Nomex®-Gore-tex®), PU-coated nylon(s) (White's and Mustang prototype dry suits), and closed-cell polymeric neoprene foam used on the CF dry suit (Rubatex® G-231-N) were acquired.

As these materials were new, it was necessary to puncture them. It was observed that it was not possible to mechanically induce hole sizes indicative of the smaller pore sizes of interest. Various approaches that were investigated included medical needles, bone drills, fine gauge wire and possibly laser or X-ray. Ultimately, holes were induced in the materials with fine tapered sewing needles (440, 500 and 850 um maximum diameter) and 30 AWG electric wire (250 um diameter).

The size of each resultant hole was approximated by viewing under a stereoscopic microscope (Zeiss®) whose right-hand eyepiece was equipped with a calibrated measuring vernier. Measurement proved to be quite difficult and due to the "ragged" nature of the holes, estimations of their size were highly subjective. Generally, the induced holes were elliptical in shape not cylindrical (Figures 4a and 4b). With several materials, puncture of the fabrics with either the wire or needles created holes where the displaced fabric formed a flap that remained attached to the perimeter of the hole. Typically, the resulting holes were smaller than the cylindrical objects used to create them. Since the needles were tapered (i.e. changing diameter), each was capable of making holes of various size. Even using an object with a fixed diameter, such as the 30 AWG wire, various sizes and shapes resulted. Such variety is likely due to material type.

No pressure differential was established across the fabric during measurement of the holes. It is anticipated that aperture size will increase and its shape will change when the fabric is tensioned by applying water or air pressure. This is likely to depend on material properties such as compressibility and elasticity. For thin materials, application of pressure will possibly increase hole size and modify its shape, particularly for stretchable materials. For a thick compressible material, it is plausible that hole size may decrease with pressure. Such variability in the size and shape of the hole as a function of pressure

certainly complicates and hence limits comparison of experimental results to predictions from Laplace's equation.

Figure 4a – Hole #2 in vulcanized rubber – Viking Pro (250X mag)

Figure 4b – Hole #1 in Nomex-Gore-tex – CF constant wear (250X mag)

Table 2 – Diving suit materials

Dry Suit Material	Hole #	Hole size* (um)	Minimum hydrostatic pressure** (psi)	Minimum air pressure*** (psi)
Vulcanized rubber (Viking Pro)	1	104 x 143	0.7 ± 0.1	0.6 ± 0.1
Vulcanized rubber (Viking Pro)	2	26 x 195	1.3 ± 0.1	1.6 ± 0.1
PU-coated nylon (Mustang dry suit)	1	78 x 104	3.8 ± 0.1	3.7 ± 0.1
PU-coated nylon (Mustang dry suit)	2	65 x 130	1.2 ± 0.1	1.6 ± 0.1
PU-coated nylon (White's dry suit)	1	Not measurable	0.7 ± 0.1	2.1 ± 0.1
PU-coated nylon (White's dry suit)	2	Not measurable	0.5 ± 0.1	1.3 ± 0.1
PU-coated nylon (White's dry suit)	3	Not measurable	0.7 ± 0.1	2.5 ± 0.1
PU-coated nylon (White's Hazmat)	1	65 x 228	0.5 ± 0.1	1.0 ± 0.1
PU-coated nylon (White's Hazmat)	2	78 x 85	0.1 ± 0.1	1.1 ± 0.1
Aramid-PTFE (CF aviation coverall)	1	78 x 143	0.1 ± 0.1	0.4 ± 0.1
Aramid-PTFE (CF aviation coverall)	2	63 x 208	0.1 ± 0.1	0.2 ± 0.2
Aramid-PTFE (CF aviation coverall)	3	Not measurable	0.1 ± 0.1	0.2 ± 0.2
Aramid-PTFE (CF aviation coverall)	4	Not measurable	0.1 ± 0.1	0.6 ± 0.1
Neoprene rubber (Rubatex G-231N)	1	Not measurable	0.5 ± 0.1	0.5 ± 0.1
Neoprene rubber (Rubatex G-231N)	2	Not measurable	0.9 ± 0.1	0.8 ± 0.1

* - Width by length (elliptical in shape)
** - Visual observation of water penetration (tap water)
*** - Visual observation of bubble formation (Ivory™ liquid soap - 2% by weight)

Of interest is the difference between minimum hydrostatic pressure and minimum air pressure for visual observation of water penetration and bubble formation. To detect leakage with most materials using soapy water, it is necessary to apply air pressure greater than the hydrostatic pressure that allows water penetration. This discrepancy between pressure was largest for both PU-coated nylon and aramid-PTFE and smallest for both vulcanized rubber and neoprene foam.

Contact angle is a function of water surface tension. Since surface tension can be altered

by the addition of a surfactant, it is plausible that the type and concentration of detergent used for soapy water and pressurized air leak testing may alter bubble formation and thus leakage detection. The ability to detect leaks using several commercially available liquid detergents (Ivory® and Sunlight®) as well as a surfactant specifically designed for gas leakage detection (La-co Visu-glo®) was investigated experimentally. There was no noticeable difference between air pressures for the onset of bubble formation with solutions of water and Ivory® or Sunlight® (at both 2% and 4% by weight). In several instances, Visu-glo® indicated leaks at lower air pressures than with the commercial liquid detergents but this was not found consistently for all materials.

Armed with a slightly better understanding of water penetration and its related variables, an investigation of alternative approaches to detecting leakage was initiated.

3.3 Small Scale Testing of Alternative Leak Detection Methods

The following four alternative test methods were investigated: Schlieren visualisation, thermal imaging, ultrasonic and trace gas detection. The following sections provide detail on the approach to each investigation as well as the results obtained and their implications to leakage detection methods for dry suits.

3.3.1 Schlieren Visualisation

Schlieren visualisation is the formation of an image by rendering visible the density gradients in a volume of flow. The image is formed by refraction and scattering from areas of varying refractive index. These variations in refractive index can be due to changes in temperature, pressure or gas type. Early Schlieren systems were used to determine variations in the refractive index of glass. More recently, they have been used to visualize supersonic flow around aircraft models in laboratory wind tunnels, convective flow and ventilation within buildings, and flow from nozzles. Mustang Survival considered it possible that such a system might be useful for detecting leakage of a gas through fabric. We hypothesised that plumes caused by pressurised gas exiting a hole through a dry suit fabric might be visualised with this technique.

The focussing Schlieren method uses no unusual or expensive optical elements, yet achieves high sensitivity at relatively low cost. A simple Schlieren visualisation apparatus was purchased (Edmund Scientific Company Part No. 71,014) that consisted of two Schlieren mirrors (4.5" diameter and 45" focal length), complete with holders and an assembled Foucault tester. The front surface of each mirror is aluminised and protected with a silicone monoxide coating. A digital video camera and television was used to view, magnify and record the resulting images (Figure 5).
Once assembled, the apparatus demonstrated the ability to visualise flow fields emanating from a heated solder iron (Figure 6), a compressed air nozzle and a warm human hand. Testing then involved determining the set of experimental conditions necessary for visualisation of the convection pattern formed by gas exiting holes in various dry suit fabrics. A custom-built, 3.5" inner diameter (8.9 cm) fabric leak test cell

equipped with a Kapton™ DC electric heater (Figure 7) was placed in the target object area of the assembled imaging apparatus. This provided the ability to conduct leakage testing with unheated and heated argon gas and/or air to pressures equivalent to 30" of H_20. Gas temperature was measured inside the pressurized region of the cell next to the fabric surface (YSI 400 thermistor).

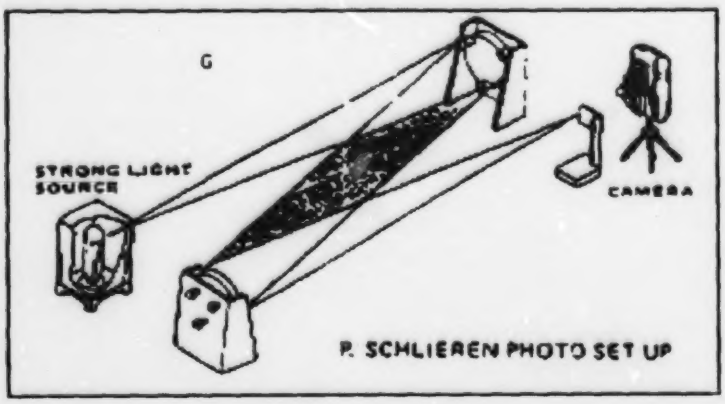

Figure 5 – Schematic of Schlieren apparatus

Figure 6 – Schlieren image of a heated soldering gun (inverted)

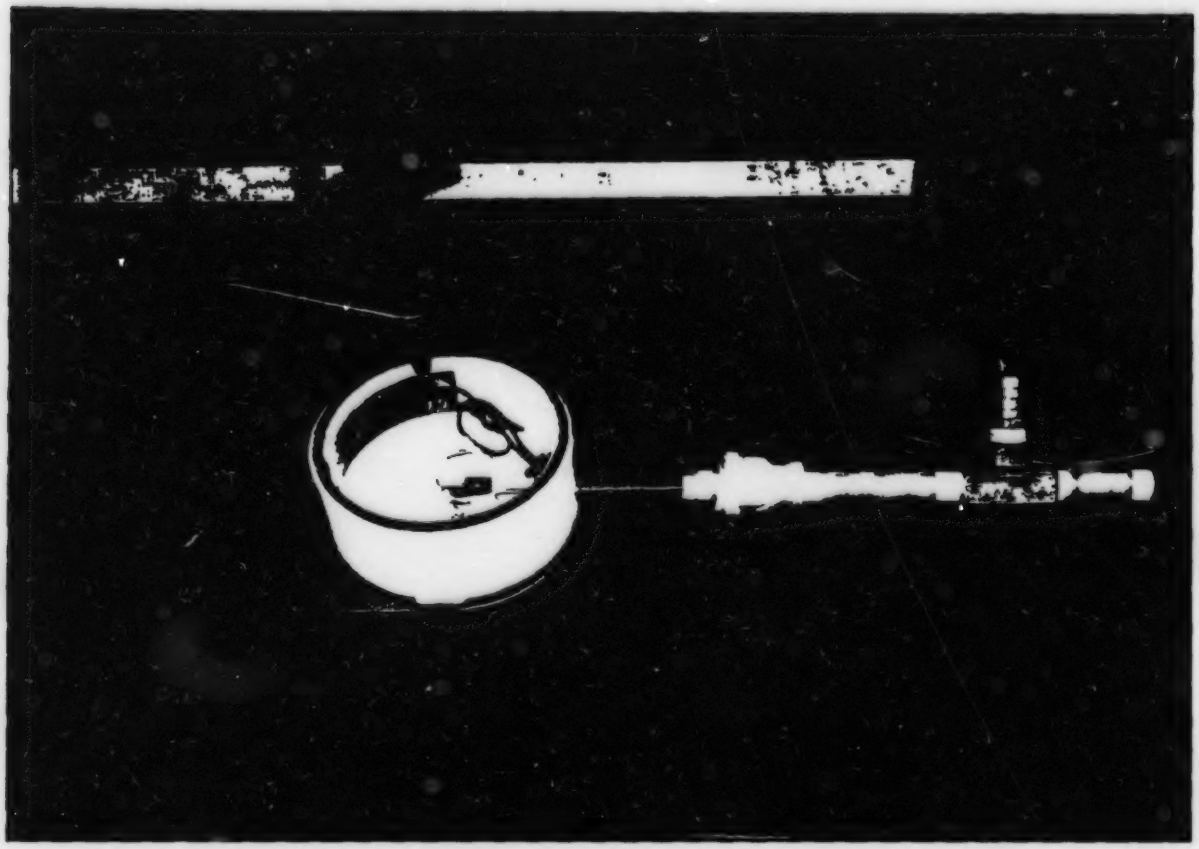

Figure 7 – Customized argon/air leak test cell

Regardless of hole size or material, we were unable to resolve an image of leakage with either argon or air at pressures upwards of 30" H_20. Heating the air and/or argon to 42C did not permit visualization of gas flow through a fabric hole either (Figure 8). Even with the textile removed from the surface of the cell, heated air or argon rising from the cell was only barely detectable (Figure 9). It is believed the minute volume of air escaping through leak of this magnitude is not sufficient to establish a visual image. It was concluded since this technique appeared not to be viable for even a small swatch of fabric, we could not recommend it as a potential method for full suit testing. It is possible that gas plumes exiting holes of this magnitude could be visualized using a Schlieren system with higher resolution but the technique would be difficult to implement on a large scale. The simple Schlieren apparatus used in this study required lengthy alignment and focussing and was prone to vibration.

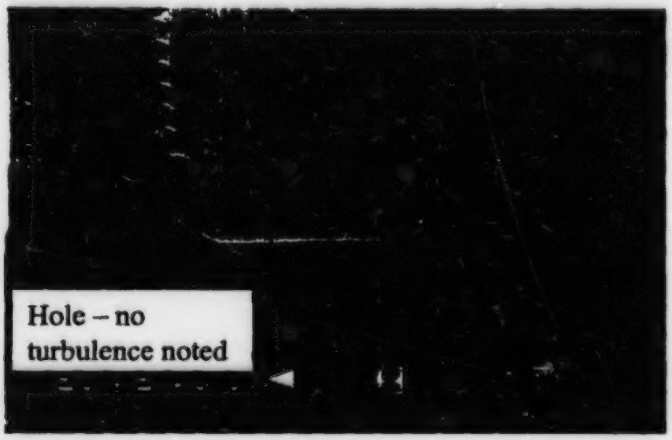

Figure 8 – Schlieren image of test cell – pressurized PU-coated nylon with hole

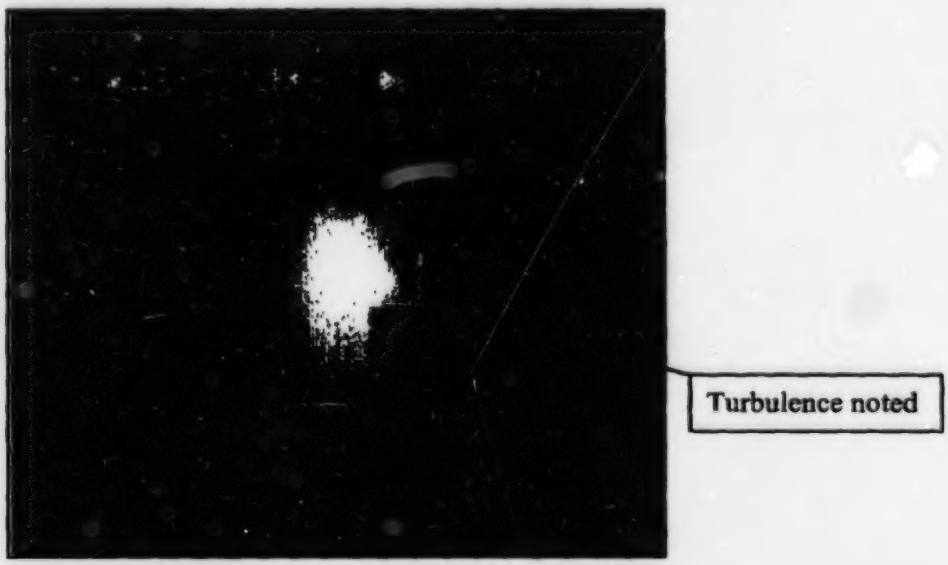

Figure 9 – Schlieren image (inverted) of test cell with fabric swatch removed

3.3.2 Thermal Imaging

It was hypothesized that leaks might be visible by photographing the entire surface area of a suit filled with a gas whose temperature differs from that of the ambient environment with a thermal imaging camera. Leaks might be visible as plumes of gas emitted from the fabric surface or as cold or hot spots.

A thermal imaging camera system (Agema-550 Elite) was rented for one month from the Academy of Infrared Thermography (tel: 250-579-7677). This hand-held camera system provided high resolution (320 x 240 detector), accurate temperature measurement and digital recording for voice comments. Colour images were saved to an integral PCMCIA card, downloaded to PC and analysed with FLIR Systems Irwin Image Viewer Version 1.01 software.

The same test cell used with Schlieren imaging was used for this portion of the investigation as it has the capacity to use both heated and unheated air or argon as a detectable medium. Using the same punctured dry suit fabrics investigated with other methods, we were unable to visualise either air or argon flow with the thermal camera. Heating the gas to 42C did not allow resolution of an image of a plume either (Figure 10), despite speculation that this would improve contrast between the plume and ambient background.

The camera did provide an image of soap bubble formation on the fabric surface (Figure 11) in the unheated cell and on the surface of a suit (Figure 12) during leakage tests using the pressurised gas and soapy water method.

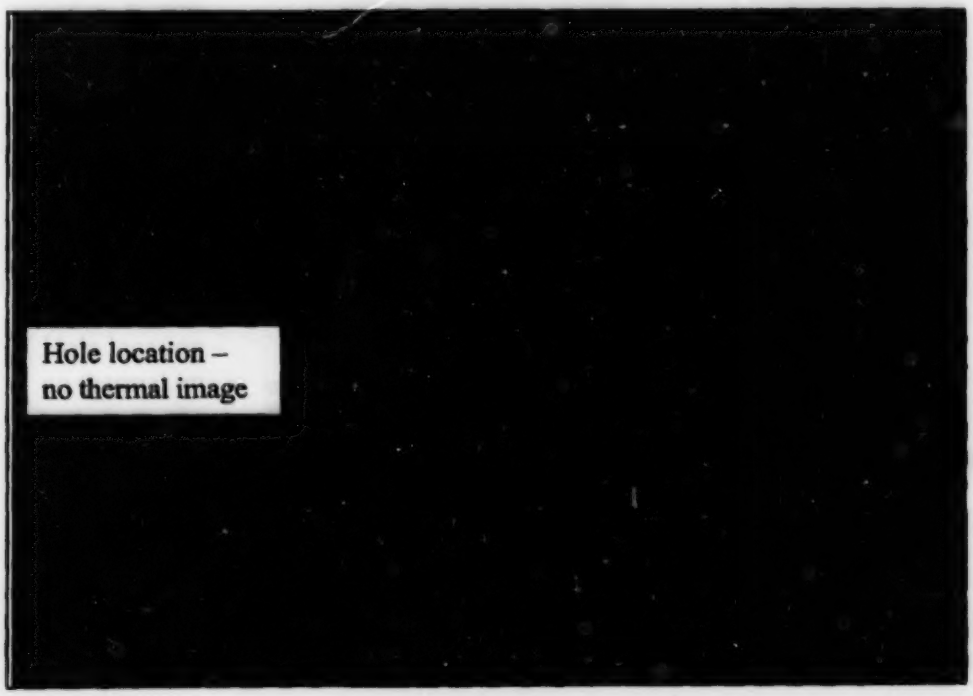

Figure 10 – Thermal imaging of dry fabric swatch with known leak

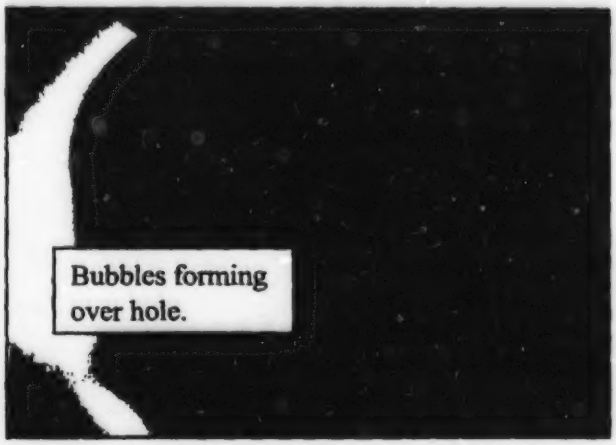

Figure 11 – Thermal image of bubbles forming on surface of fabric swatch

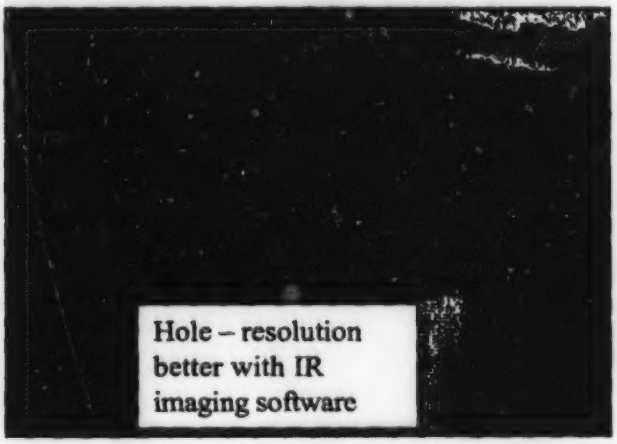

Figure 12 – Thermal image of a hole on a wetted PU-nylon dry suit (OC4000)

It was observed during one test that an actual hole in a PU-coated nylon dry suit was visible as a thermal image but only for a moment (approximate duration of one second). This instance occurred just after soapy water had been applied to the exterior of the dry suit. As the layer of water had nearly completely run-off the suit's exterior, the hole became visible as the exiting air displaced the thin layer of water overtop of the hole. A thin layer of water remained on the fabric adjacent to the hole for a brief period.

Since bubbles can be located with the naked eye, these camera observations are of little practical significance. Based on the inability of this particular camera to resolve leaks of interest, thermal imaging was not investigated further.

3.3.3 Ultrasonic Detection

Ultrasonics is used commercially as a means of leak detection. The term "ultrasonics" deals with the branch of acoustics whose frequency waves are above the highest frequency audible to the human ears (specifically, frequencies greater than 16 kHz). Various mechanisms produce ultrasound in the 45 kHz range, which is the frequency characteristic of the peak amplitude for most leaks. These mechanisms are turbulent fluid flow, liquid movement, mechanical movement, sound generators, and electrical discharge. Turbulent flow of a fluid across a pressure boundary creates acoustic waves. Turbulent flow often occurs through holes with a diameter of 0.38 mm to 12.7 um. Depending on the sensitivity of the instrument used for ultrasonic detection, pressure differentials of the order of 5 psi are indicative of typical lower limits of detectability. Use of low viscosity fluids, such as helium, allows for greater turbulent energy and hence may allow the location of leaks that could not be found with air. Likewise, greater velocity (the complement of a greater pressure differential) can also increase turbulent energy and hence detectability.

Liquid movement, mechanical movement and electrical discharge are mechanisms not relevant to leakage. While the mechanism termed "liquid movement" includes the detectable ultrasonic energy produced by small bubbles as they burst, bubbles formed with soapy water solution during pressurized gas testing are not detectable. These are generally large bubbles, which produce low energy levels.

An ultrasonic sound generator and detector, matched to the same frequency, can be used to test the leak-tight integrity of unpressurized containers. When the generator is used inside a closed container with walls that reflect rather than dampen noise the ultrasonic signals will pass through small leaks and can be detected. The technique has been used on welded seams, airplane components, condenser tubes, and large tanks. It is possible that it will not be applicable to leakage testing of clothing as most textiles dampen noise rather than reflect it.

A hand-held ultrasonic detector (SDT International Model 170) was acquired for investigation as a means of leakage detection. This particular detector worked from one to 200 kHz and required a minimum flow of $6.7*10^{-2}$ ml/s for detection. Using the heated gas leakage test cell, the dry suit fabrics investigated previously were tested to investigate the ability to detect leakage with passive ultrasonics.

As anticipated, passive detection required inflation pressures in excess of 2.0 psi to produce noticeable differences in sound intensity. A swatch of Nomex™-Gore-tex™ inflated with air to 5 psi produced 15 dB over the regions without leakage and 33 dB directly over the leak itself. Unfortunately, this pressure level is too high for most dry suits to withstand structurally.

A CF constant wear aircrew immersion suit (Nomex™-Gore-tex™) was punctured with a pin in several locations on the chest to determine if such holes could be detected using passive ultrasonic. Constraint straps were fastened around the suit's latex neck seal to

limit expansion and clamps were placed above the latex wrist seals in order to seal the suit's arms. A customised jig designed by Mustang was used for blocking neck seal openings during leak testing. While the method identified a leak, the hole was relatively large (leaked at less than 0.2 psi hydrostatic pressure) and finding smaller holes of concern would require pressures in excess of 2.0 psi.

It was desired to test a more robust dry suit built from polyurethane-coated nylon (Ocean Commander™) using passive ultrasonics, but unfortunately, forming an airtight seal between the suit's hood and the neck seal jig was not possible. Such major leaks must be prevented or else the ultrasonic noise they generate masks other smaller leaks. It was noted that it was difficult to manoeuvre the sensing wand's tip at a fixed distance of approximately 2.54 cm (1") above the suit exterior, as recommended by the manufacturer, without accidentally making physical contact. Contact results in a very loud scratching noise.

An ultrasound generator (SDT International) was acquired as it was speculated that its use could eliminate the need for inflating the suits to such high pressure. The generator produced two different 200 mW signals (38.4 ± 2 kHz). The dimensions of the ultrasound generator were such that it could not fit inside our air leakage test cells. Active ultrasonic testing was limited to placing the generator inside dry suits. A CF constant wear aircrew immersion suit with three pinhole-sized leaks in the chest region that leaked at less than 0.2 psi hydrostatic pressure was tested first. The suit was tested at varied pressures with the generator set on LO and HI output. Table 3 contains the mean decibel level measured outside of various regions of the suit with the generator on HI and the suit inflated to 1 psi.

The results indicated that the decibel level was 23.9% greater (10.7 dB) overtop of regions with holes than regions without holes (no holes = 44.8 ± 3.7 dB; holes #1 and #2 = 55.5 ± 5.2 dB). We noted that both hole #1 and #2 were located directly above the sound generator. Concerned that leaks located at a greater distance from the generator would not be as detectable as hole 1 and 2, we introduced hole #3 at the elbow of the garment's right sleeve. Indeed, the sound level at hole #3 was lower; it was only 46.9 ± 1.3 dB, essentially the same as a region without holes.

The CF aircrew immersion suit tested is constructed of a thin waterproof, vapour permeable material. It is possible that a greater difference between decibel levels (over a hole vs. away from a hole) would be obtained with a garment constructed of thicker and hence less acoustically transparent material. A CF diver's dry suit with a hole introduced through its 7.1 mm thick Rubatex G-231N was investigated in the same manner as the CF aircrew immersion suit. Unfortunately, there was even less difference between the decibel level over a hole versus away from a hole. Directly over a hole was measured at 19.9 ± 0.3 dB; other regions of the suit were 19.4 ± 0.2 dB. These noise levels are essentially equal to that of the ambient background.

Table 3 – Active ultrasonic noise level at exterior of CF aircrew immersion suit

Region	*Decibel Level (dB)*
Left sock	41.1 ± 2.0
Right sock	40.4 ± 0.1
Left thigh	45.1 ± 1.7
Right thigh	41.5 ± 0.7
Crotch (urinal zipper)	46.0 ± 3.7
Left side of torso	46.5 ± 0.4
Right side of torso	43.3 ± 1.5
Centre of entry zipper	49.3 ± 3.6
Left underarm	47.9 ± 2.6
Right underarm	44.9 ± 1.5
Left wrist	41.4 ± 1.3
Right wrist	40.7 ± 1.5
Neck seal	49.7 ± 1.3
Hole #1	53.9 ± 0.6
Hole #2	55.2 ± 1.5
Hole #3	46.9 ± 1.3

Another potential technique recommended by SDT, is to place the vessel of interest underwater so that bubble formation, which is not affected by surfactant, can be detected. Unfortunately, this approach would simply provide pass/fail criteria, not localisation of leaks. Based on the swatch and full suit testing, both passive and active ultrasonic detection was ruled out as a method of leakage testing for dry suits.

3.3.4 Trace gas detection

The trace gas method involves filling the ambient environment with a trace gas and "sniffing" inside the suit for gas ingress or alternatively, filling the suit with trace gas and "sniffing" outside the suit for gas egress. "Sniffing" or detecting of a trace gas is typically done by electronic means ranging from simple hand-held devices to complex rack-mountable systems. Electronic gas detectors are used regularly by gas line and refrigeration technicians. Trace gas detection has also been used successfully by researchers to determine water vapour permeability of clothing systems.

Mustang Survival has a hand-held gas detector (Ion Science Ltd. Model 8500 Type B4) which can detect the presence of a range of gases with varied sensitivity. The device provides detection of hydrogen, helium, argon, methane, carbon dioxide, sulphur hexafluoride, R12, R1301, R134A and R11 with the minimum detectable level ranging from $4x10^{-5}$ to $5x10^{-4}$ $ml \cdot sec^{-1}$, depending on the gas type. The device has a response/recovery time of one second and can operated in temperatures ranging from zero to 50°C. The detector has the ability to be "zeroed" to work in environments with varying background levels of trace gas. We ruled out hydrogen, methane and carbon dioxide for safety reasons. Sulphur hexafluoride, while inert, non-toxic and very stable, is

expensive due to its current world shortage and is a very potent greenhouse gas with very high global warming potential hence was eliminated as a potential candidate due to these shortcomings. The refrigeration gases were eliminated as candidates for similar reasons. This left argon gas as the only potential candidate for use with this particular detector. To detect argon, the detector requires a minimum useable level of 2×10^{-4} ml·s^{-1}.

When swatches of dry suit fabric were tested with pressurised argon gas, the device was capable of detecting small leaks at very low pressures. Hole #1 introduced through Viking vulcanised rubber was known to leak water at 0.7 psi hydrostatic, a third of the pressure possibly encountered diving. For comparison, the flow of pure unheated argon gas through this hole, as a function of applied pressure was measured with the hand-held detector (Figure 13).

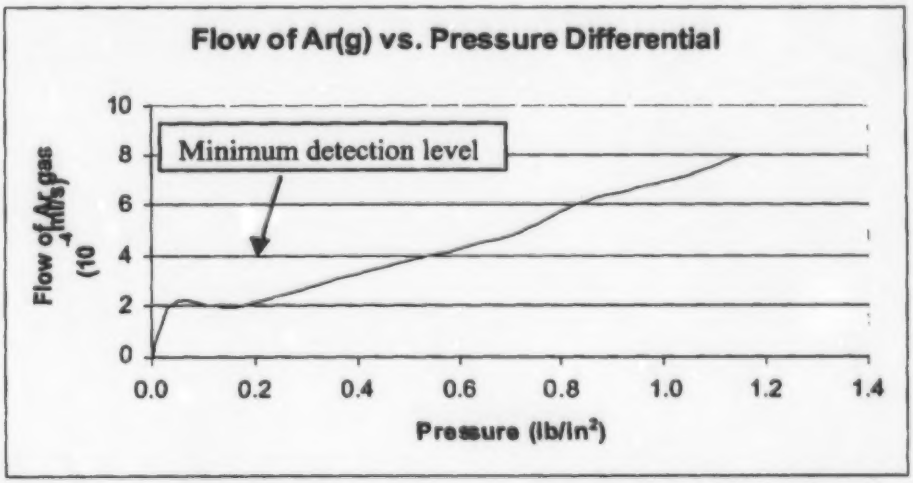

Figure 13 – Detected Argon Flow vs. Pressure for Viking Fabric

With 0.7 psi of argon, the leak was easily detectable when the hand-held was held above the hole. Note the detector is only capable of measuring argon flow as low as 2.0×10^{-4} ml·s^{-1}. This flow cut-off occurred at a pressure differential of 0.1 psi (5 mmHg). This means that argon flow was detectable through this particular hole with trace gas method at a lower pressure than with hydrostatic or soapy water-pressurised air test methods. Based on the potential increase in detection sensitivity and the fact that the method is relatively safe and leaves the suit dry, trace gas was the only one of the four alternative methods considered for further investigation.

From the series of tests conducted on fabric samples the following observations were made regarding the operational envelope of the argon gas detector:

- As little as 5 mmHg (0.1 psi) was sufficient pressure to detect argon escaping from a hole approximately 10-30 um in diameter, but the detector could be no more than 10-15 mm above the hole and no more than 5 mm laterally from the hole;
- Argon gas was increasingly detectable with increased pressure as a result of the higher flow rate that ensued through any hole; and
- Use of a vacuum pump to increase the pressure gradient across a hole did not yield any noticeable improvement in argon gas detection as it was speculated that increasing the flow to the gas detector only diluted the argon concentration by disproportionately increasing the amount of air that was being drawn into the sensor.

Once fabric sample tests had determined the limits on the operating conditions of the detector, an inflatable personal flotation device (PFD) was leak tested to determine the suitability of using an argon gas "accumulation chamber" as an instrument for rapid pass/fail screening. An "accumulation chamber" is a sealed enclosure used to contain leaking gas such that its concentration may increase to a detectable level.

Initially, the PFD was inflated with argon gas to a pressure of 50 mmHg (1 psi) and its surface scanned manually with a handheld leak detector to verify the presence and location of any holes. Having determined that the handheld detector was capable of detecting argon gas leaking from small pinholes (order of magnitude that would leak water), a further investigation was conducted to determine whether such holes would be detectable when the PFD was placed within a sealed chamber. This was accomplished by placing an argon-inflated PFD within a heat-sealed polyethylene bag. The PFD was surrounded by a perforated tubing network and spacer material to ensure the ability to continuously draw air samples from within the bag for hand-held detection of argon. Tests were conducted to determine whether the accumulation chamber should be inflated or evacuated and whether it was possible to estimate the magnitude of any detected leaks. This involved attempting to detect leaks under the following five test conditions:

1. Argon pressure = 50 mm Hg, bag inflated, no holes;
2. Argon pressure = 50 mm Hg, bag inflated, 1 hole;
3. Argon pressure = 50 mm Hg, bag inflated, 3 holes;
4. Argon pressure = 50 mm Hg, bag evacuated, 3 holes; and
5. Argon pressure = 50 mm Hg, bag inflated, 5 holes.

Partial evacuation of the air within the bag was performed using a laboratory vacuum pump until the polyethylene bag wrapped firmly around the spacer material. The system was then allowed to equalise to atmospheric pressure. In cases where the bag was inflated, inflation pressures were approximately 0.1 psi (5 mmHg).
The results of small-scale tests conducted using a PFD illustrate the detected leak rate as a function of time for each of five test conditions (Figure 14 - note that the negative sign

on the flow rate indicates leakage). Both the presence and magnitude of a leak were readily detectable using a sealed accumulation chamber. While there was noticeable variability in the magnitudes of the measured argon concentrations for any given number of holes, in general there was a correlation between the measured leak at any time and the size (or number) of holes producing the leak. Using this screening technique a general pass/fail grade was assigned within 30-60 s on the PFD used in this test.

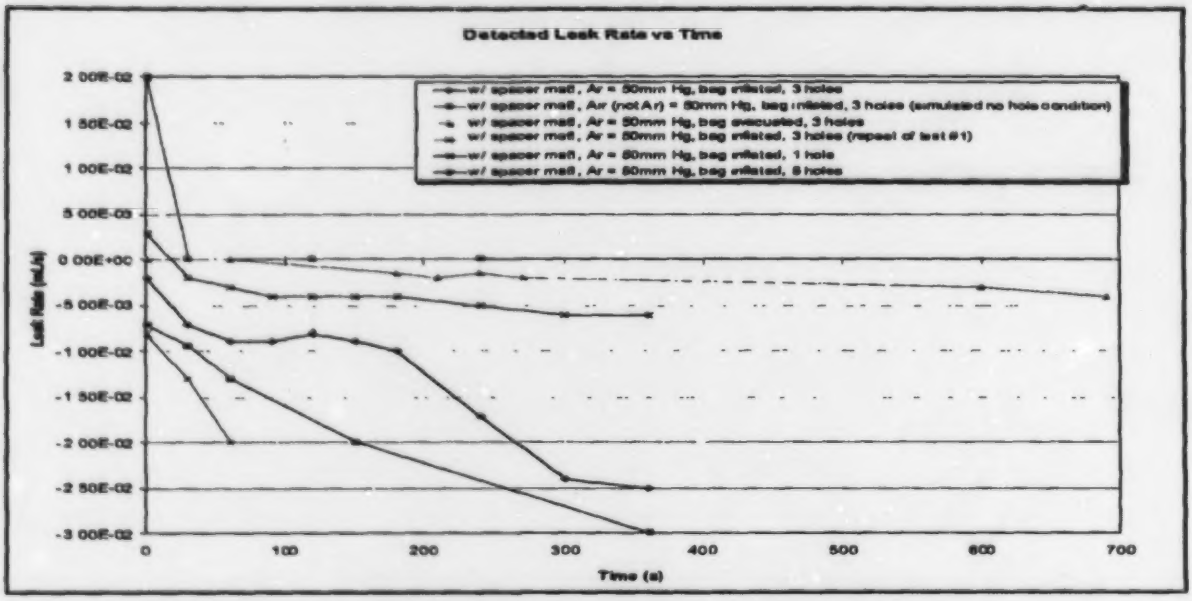

Figure 14 – Leakage rates detected for an argon-inflated PFD

3.4 Full Suit Testing

A full-scale apparatus capable of trace gas leak detecting entire suits was envisaged. Ideally, the chamber would provide regional leak detection and location. If regional detection and location was not possible, a fall-back approach may be to use the chamber for simple pass/fail screening of suits.

A full-scale leak test chamber was designed and constructed (Figure 15). The chamber shell was constructed of plywood with an angle iron support frame. The inside of the chamber was shaped to conform to the outer profile of inflated Mustang Ocean Commander™ and Ice Commander™ suits. This inner surface was lined with an airtight fabric shell that had 128 holes (1/4" diameter) distributed over its surface.

Each of the 128 gas sampling holes were connected to 1 m lengths of 1/4" vinyl tubing that collected into four manifolds, each housing 32 tubes. A main sampling tube extended from the head of each of the four manifolds. By rotating a given manifold head, each of the 32 tubes could be sampled to detect the presence of argon gas leaking from the suit interior to the chamber. Initial tests involved placing an Ocean Commander, inflated to 0.1 psi with argon, within the chamber and sampling the tubing at each of the four manifolds with the hand-held detector, to determine if argon was detectable and to quantify any time lag between the inflation of the suit and the detection of a leak.

Another set of tests involved inflating the suit and subsequently sampling the chamber air at periodic intervals to monitor the accumulation of argon as a function of time to determine if a visible correlation existed between the rate of argon accumulation and the size or number of holes in the suit.

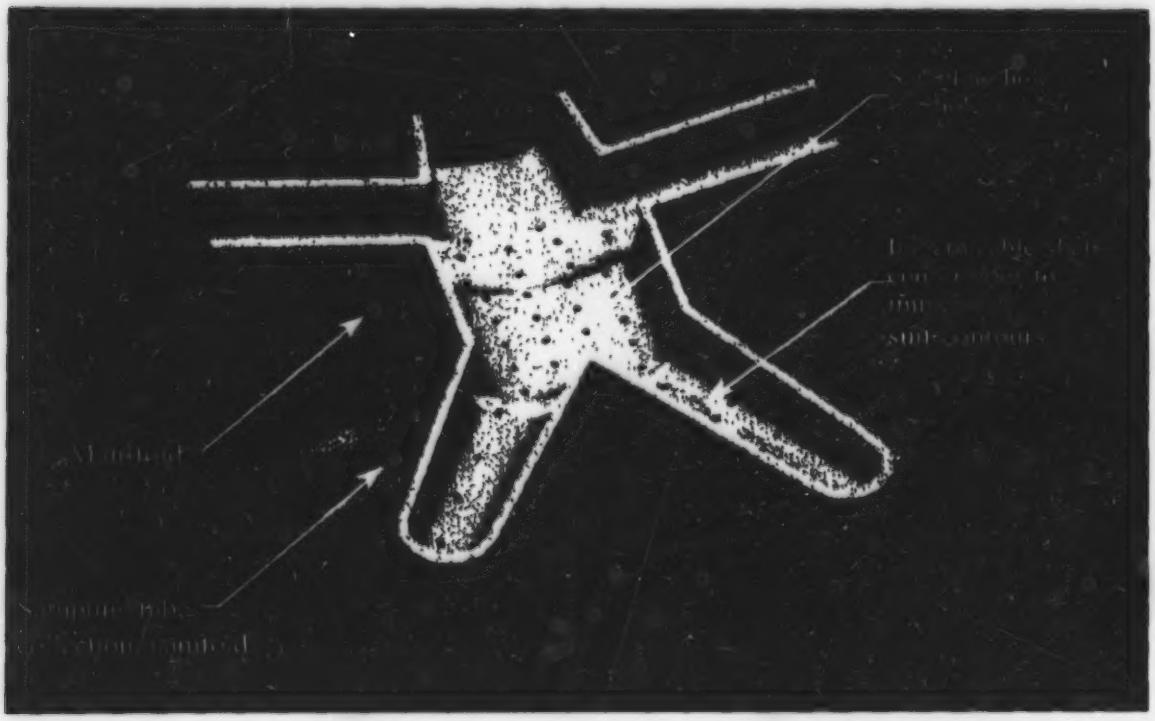

Figure 15 - Full-Scale Argon Accumulation/Sampling Chamber ("The Coffin")

The results of full-scale trace gas leakage testing chamber implementation and testing were somewhat disappointing. Initial attempts to sample argon gas from each of the four collection manifolds were unsuccessful, as it was determined that the seal between the tubing and the manifold cover was inadequate. Upon removing the manifold cover and sampling the gas directly from the end of each sampling tube, argon was detectable but with a time lag of approximately 30-60 s depending on the magnitude of the leak. This delay was attributed to the relatively long distance (1 m) that the gas sample had to travel to reach the detector and hence could not be avoided without a major redesign of the

chamber. Sampling 128 tubes at 60 seconds per tube would take at least 2.1 hrs, a duration that is impractical. In addition to the time lag, only large argon leaks could be detected. Small holes produced low, undetectable argon concentrations. This was likely due to dilution of the argon by air surrounding the garment.

Additionally, it was noted that the argon gas, being denser than air (Δ = 1.78 kg/m^3), settled rapidly and was only detectable by those sampling tubes located along the bottom of the accumulation chamber. This severely limited the ability to gain specific information regarding leak origin it was decided to instead evaluate the chamber's ability to obtain leak origin information from five large regions (two arms, two legs, and torso). This was accomplished by joining together four sampling tubes (all located along the bottom of the test chamber) in each of the five regions and sampling the gas from the five resulting "regional" tubes. Unfortunately, while this was able to detect large argon leaks (i.e. leakage from around the neck and wrist seals of the suit), it was not capable of detecting the small leaks produced by pin holes.

As a final attempt to gain regional leak information for a suit, each of the five regions that had been tested before were partitioned to prevent the gas in one region from drifting into others. Again the gas was sampled in each region from four tubes located at the bottom of the chamber, but small leaks remained undetectable. Figure 16 illustrates the detected leak rate measured immediately above a hole of 10-30 micron in diameter (labelled "Actual Leak") and through the gas sampling tubes. While the detected leak rate increased after approximately one hour, it did not sufficiently approach the actual leak rate necessary to be considered positive leak identification.

To increase gas detection capabilities, a gas sensor based on thermal conductivity detection was purchased (Gow-Mac Instrument Co. Part No. 10-133). This sensor required a mimimum flow of 8.3 x 10^{-5} ml/s flow hence had higher sensitivity than the hand-held detector. Using a tee and tubing, the sensor was placed outside the chamber in-line with the airflow. Electronics were constructed to power the sensor and measure its electronic output. Experiments similar to those conducted above were repeated. However, the same performance deficiencies (lag, gas settling and dilution) as observed with the hand-held detector were noted.

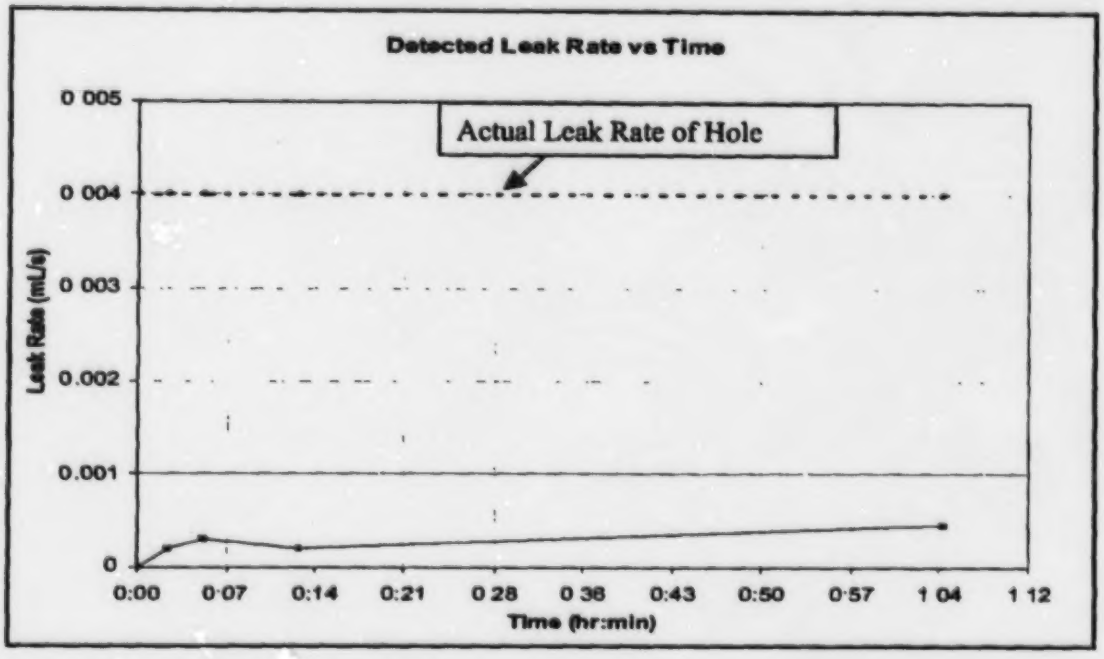

Figure 16 – Detected vs. Actual Argon Leakage Rate for Full Suit

4.0 DISCUSSION

Testing with filtration membranes indicated that a hole less than 5 um in diameter is not likely to allow water leakage at pressures indicative of those experienced with normal dry suit use.

The test results indicate that there is a discrepancy between the required pressure differential for water and air (in the presence of soapy water) penetration of a hole in fabric. The implication of this finding is that for certain fabrics, a higher pressure (in the order of 2 psi) will be required to detect leakage using a method of bubble detection (e.g. suit inflation with air and application of soapy water) than with hydrostatic test methods. Suit inflation pressures in the order of 2 psi will be necessary to detect such holes using soapy water methods. Most dry suits risk being damaged at such high inflation pressures, thus are traditionally tested at pressures in the order of 0.2 to 0.5 psi, which could leave holes undetected.

The alternative methods of leak detection are not viable. Schlieren visualisation and thermal imaging failed to yield results demonstrating detection of leakage. Passive ultrasonics did demonstrate the ability to detect leakage of holes at inflation pressures between 2 to 5 psi, but again, these are too high for most suits to withstand. Active ultrasonics did demonstrate the ability to detect leakage of holes on suits constructed of thin material, so long as the sound generator was located near the leaks but with thick

neoprene suits this method did not detect holes.

Argon gas detection offers a potentially viable method for leakage detection. It was demonstrated to find leaks in small swatches if the detector was in close proximity of the hole. Our attempts at designing and constructing a full-scale system, while not ultimately successful, offer valuable information to future chamber designs. An improved chamber design would require the following:

- Minimisation of the volume of air surrounding the suit (reduce dilution);
- Shorter tubing lengths between sample point and gas sensor (reduced response time);
- Multiple sensors located directly next to sampling points (reduced response time and gas dilution);
- Sensors with higher sensitivity and faster response time (increased sensitivity); and
- Use alternative trace gases with lower density (reduced settling effect, improved localisation).

If a function leak test system based on trace gas could be designed for suits, it may offer improved sensitivity, low suit inflation pressure, and would allow the suit to remain dry.

5.0 CONCLUSIONS

A literature review of existing leakage detection methods failed to find any novel method relevent to diver's dry suits. Testing of immersion suits is typically conducted by either filling the suit with water and inspecting the exterior for liquid breakthrough or by filling the suit with pressurized gas, rinsing the exterior with soapy water and inspecting for the formation of bubbles.

Penetration of liquid through porous mediums is described by Laplace's equation. Various membrane types and pore sizes were tested for hydrostatic resistance. These experiments suggest that smallest holes of concern to a diver are in the order of 5 um in diameter. In several cases, the pressure at which water penetration was noted experimentally was less than predicted theoretically. In several cases, the air pressure at which holes through the same membranes were detectable by bubble formation upon application of soapy water was greater than the hydrostatic pressure for water leakage. It is likely this has implications to existing test methods. It is recommended that air pressures used for soapy water testing, exceed the hydrostatic pressure for which the material is subjected to in actual use.

Materials commonly used for the construction of dry suit shells were investigated by both hydrostatic and air-soap methods. These materials were punctured mechanically with pins and fine wire. Again, the difference between hydrostatic pressure for water penetration and air pressure for bubble formation was noted. This difference was greater with polyurethane-coated nylon and an aramid-PTFE laminate than neoprene foam and vulcanized rubber.

Four alternative methods of detecting leakage were investigated. Schlieren visualisation failed to provide an image of air or argon exiting a leak. Heating either gas 20C above ambient and increasing pressure to 1 psi did not permit visualisation. Thermal imaging also failed to provide a visual image of a gas plume but was capable of visualizing bubbles forming when soapy water is applied to the suit. In one instance, a known leak was resolved thermally. This occurred as the thin layer of water running off a suit was displaced immediately overtop the hole. It appeared as a region colder than the surrounding fabric. Passive ultrasonic detection was capable of detecting leaks in suits but required suit inflation pressures that are too high (2 to 5 psi). Such pressures can easily damage the elastic materials used in dry suits. Active ultrasonics was capable of resolving a hole in dry suit, if the materials were thin and if the sound generator was in close proximity of the hole. It did not work on suits made of 7 mm neoprene.

Detection of argon gas using thermal conductivity means was found to be the only alternative approach to fabric leak detection worthy of further investigation. With fabric swatches, a hand-held detector was capable of detecting small leaks (10–30 um) at pressures as low as 0.1 psi (5 mmHg). The device had to be in close proximity to the leak (15 mm above and 5 mm laterally from hole). With a hand-held detector, it was possible to detect leakage from an argon-filled inflatable PFD enclosed in a flexible bag. Based on these preliminary results, a full-scale suit leakage test chamber was designed

and constructed. Full suit testing indicated three key design deficiencies. The large volume of air surrounding the suit and the long tubing lengths causes a dilution of argon gas to undetectable levels and a long detector response time. This delay potentially allowing argon to accumulate to detectable levels, also allows the dense argon to settle to the lowest locations of the chamber. This makes localisation of leaks very difficult as gas detection occurs at sample points located away from the actual leak.

It was concluded that to obtain any regional information concerning leak location on dry suits with argon trace gas, the only reliable approach is to scan the entire surface area with a hand-held gas detector placed immediately against the surface of the suit.

6.0 RECOMMENDATIONS

If another chamber similar to the one constructed in this investigation is developed, greater care should be taken to ensure that the impermeable liner conforms precisely with the contours of the suit being tested either by using a stretch fabric or some mechanical means of wrapping tightly around the suit. By reducing the volume of air that surrounds the suit any leaking argon will not be diluted as severely as it was with the present chamber design resulting in increased sensitivity. Additionally, the distance between the sampling hole location and the trace gas detector element should be minimised to reduce the time lag in leak detection.

Alternatively, should a different chamber design be investigated, some mechanical means of ensuring that the argon detector remain in close proximity to the suit should be incorporated (i.e. with proximity sensors mounted on a translating and rotating arm mechanism). This would allow the acquisition of more specific regional information than the present design although it would be much more technically challenging and expensive.

In either of the two approaches listed above, great care must be taken to ensure that all neck and wrist openings are absolutely airtight since leakage from a poorly secured seal could mask any smaller holes in the vicinity. This would likely involve a redesign of the existing neck seal clamp or possibly having the neck seal protrude from the chamber to prevent it from contaminating the chamber air with argon.

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DOCUMENT CONTROL DATA SHEET

1a. PERFORMING AGENCY Mustang Survival Corp Research Division, 3810 Jacombs Road, Richmond, B C., Canada, V6V1Y6	2 SECURITY CLASSIFICATION UNCLASSIFIED
1b. PUBLISHING AGENCY DCIEM	

3. TITLE

(U) An Investigation of Current and Alternative Methods for Testing the Waterproofness of Dry Suits

4. AUTHORS

Uglene,Wendell V ;Iaconis,Jean-Louis

5 DATE OF PUBLICATION September 21 , 2000	6 NO OF PAGES 29

7. DESCRIPTIVE NOTES

8. SPONSORING/MONITORING/CONTRACTING/TASKING AGENCY
Sponsoring Agency.
Monitoring Agency.
Contracting Agency . DCIEM
Tasking Agency:

9. ORIGINATORS DOCUMENT NUMBER Contract Report 2001-005	10 CONTRACT GRANT AND/OR PROJECT NO PWGSC Contract No W7711-6-7479-04	11. OTHER DOCUMENT NOS

12 DOCUMENT RELEASABILITY

Unlimited distribution

13 DOCUMENT ANNOUNCEMENT

Unlimited

14 ABSTRACT

(U) Dry suits are worn by personnel from various civilian agencies for protection against exposure to water during immersion. Protection against chemical/biological contamination and insulation from cold water rely on the integrity of a suit's waterproofing Dry suits may require test inspection to verify their integrity during both construction and actual use. While there are numerous standard leak test methods for fabric swatches, only a few exist for full suit systems Literature review indicated testing of immersion suits is typically conducted by either filling the suit with water and inspecting its exterior for liquid breakthrough or by filling it with pressurized gas, rinsing its exterior with soapy water and inspecting for bubble formation The report details an investigation into four alternative leak detection methods for dry suits

15 KEYWORDS, DESCRIPTORS or IDENTIFIERS

(U) waterproofness,dry suit;leak test,DCIEM,alternative leak testing method,immersion dry suit;water leakage,pressure differential;effect of surfactant type;effect of liquid transport via wicking,coated fabric;laminated fabric;closed-cell foam;waterproof integrity;chemical/biological contamination, membrane,practical investigation of leakage;hydrostatic leak test cell,Laplace;PTFE,stretchable material,Schlieren visualisation;thermal imaging,ultrasonic detection,trace gas detection;argon leak test cell;PU-coated nylon;vulcanised rubber;full suit testing

#515720

CA011072

CA011072

DOCUMENT REVIEW PANEL PUBLICATION RECORD

A. BIBLIOGRAPHIC DATA	
1. PERFORMING AGENCY(IES) Mustang Survival Corp. Research Division, 3810 Jacombs Road, Richmond, B.C., Canada, V6V1Y6	2 CONTRACT and/or PROJECT NO PWGSC Contract No. W7711-6-7479-04
3 SPONSOR (DND Project Officer or Directorate)	4. PUBLICATION SERIES and NO . Contract Report 2001-005
5. TITLE : (U) An Investigation of Current and Alternative Methods for Testing the Waterproofness of Dry Suits	
6 PERSONAL AUTHORS : Uglene,Wendell V.;Iaconis,Jean-Louis	7. DATE OF PUBLICATION : September 21 , 2000
8. PUBLISHING AGENCY (Name of Establishment) DCIEM	
B. SECURITY CLASSIFICATION / LIMITATION INFORMATION	
9a Overall SECURITY Classification or DESIGNATION of document: UNCLASSIFIED	9b. DOCUMENT REVIEW DATE : January 1 ,
10a. OFFICIAL WARNING TERM (e g. Canada/US Eyes Only)	
10b.Reasons for Classification or warning term:	
11a. DETAILS OF FOREIGN CLASSIFIED INFORMATION	

Country of Origin	Highest Level	PAGES ON WHICH CLASSIFIED OR DESIGNATED INFORMATION IS CONTAINED		
		Text	Tables/Figures	Classified Titles Cited

11b. FOREIGN CLASSIFIED REFERENCES	
12 DOCUMENT RELEASABILITY Unlimited distribution	13. APPROVED COUNTRIES
14. DOCUMENT ANNOUNCEMENT Unlimited	
15. REASON FOR NO ANNOUNCEMENT	
D. AUTHORIZATION	
16. Meeting number and date of action of Establishment or HQ Document Review Panel. 1-2001 (DRP Meeting No.) 2001/02/21 (Date) Approved by :	